Silicon nanomembrane based photonic crystal waveguide true-time-delay lines on a glass substrate

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ABSTRACT

We demonstrate photonic crystal waveguide true-time-delay lines fabricated on a large area (>2cm x 2cm) silicon nanomembrane transferred onto a glass substrate. The photonic crystal waveguides are designed to provide large time delay values within a short length. 17.1 µm x 10 µm subwavelength grating (SWG) couplers are employed in order to enable efficient light coupling from and to a fiber. Photonic crystal tapers are implemented at the strip-photonic crystal waveguide interfaces to minimize loss and provide larger time delay values. A large group index of ~28.5 is calculated from the measurement data, thus indicating achievability of time delay larger than 58ps per millimeter length of the delay line within a tuning range of 20nm.

Key words: photonic crystal waveguide, true-time-delay,subwavelength grating, silicon nanomembranes, flexible photonics.

1. INTRODUCTION

Photonic crystal waveguides (PCWs) offer strong optical confinement and slow light enhanced interactions, which enable realization of many miniaturized and highly efficient devices [1-6]. High dispersion and slow-light PCWs will greatly enable the development of compact systems, especially for applications requiring strict control on payload, such as phased array antenna (PAA) systems [7] in air-borne platforms. It is well known that photonic true-time-delay (TTD) systems enable broadband operation of PAA due to their inherent characteristic of providing a linear response of phase-frequency relationship across the entire operating bandwidth of the radio-frequency (RF) signal [8]. Furthermore, if such systems can be developed conformally on any surface, it will greatly help in reducing the overall weight of the system.

Nanomembrane research has attracted a lot of attention over the last decade, due to the ability to develop light-weight and conformal devices [9-11]. Flexible and conformal electronic devices promise tremendous applications in the areas of medicine, imaging and sensing, which are unthinkable using conventional material systems and processes. Benefits on a similar scale are also foreseeable for photonic components however, the difficulty in transferring intricate photonic devices, in addition to the unavailability of a suitable light coupling scheme on foreign substrates, has deterred widespread developmental activities. Previous attempts have demonstrated unique transfer schemes, utilizing which, silicon nanomembrane based photonic devices have been developed on flexible as well as on rigid substrates [12-14]. However, light

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coupling into these devices was based on butt coupling, which is very difficult to realize on different substrates. In order to address the light coupling problem, we have previously demonstrate high coupling efficiency of up to 37.2% utilizing SWG on transferred SiNM [15]. Therefore, by combining slow-light PCWs and nanomembrane transfer technology, extremely compact and light weight conformal optical beamforming systems can be achieved.

We have previously developed and demonstrated compact PCW based TTD lines on silicon-on-insulator (SOI) chip. A 1x4 PCW delay line was developed, and a large time delay up to 216ps was measured within 20nm tuning of wavelength [16]. In this paper, we demonstrate the development of silicon nanomembrane based photonic crystal waveguides that can be used for developing lightweight, conformal, and compact true-time-delay systems on any substrate. A scheme that satisfactorily addresses both SiNM transfer, and light coupling issues, which can be applicable for developing conformal silicon photonic devices,is presented. First, a scheme to transfer defect free large area (2cm x 2cm) SiNM on a glass substrate is presented. Next, a 100μm long silicon photonic crystal waveguide (PCW) is patterned on the transferred nanomembrane, together with subwavelength grating couplers [15]. Furthermore, an integrated Fourier transform interferometer is developed to accurately measure the group index of the transferred PCW, and demonstrate slow-light effect.

2. FABRICATION

A home-made bonding tool is utilized to first bond a 2cm x 2cm SOI (675 μm handle, 3 μm BOX, 250 nm device layer) onto a 1mm thick glass slide. Before bonding, the SOI and glass slide are spin-coated with 5 μm thick SU-8 layer. The native oxide on the surface of SOI is removed with buffered oxide etchant (BOE). The samples are soft baked at 95 ^{o}C to evaporate the solvent. Then, the SOI chip is put upside down on the glass slide andplaced in anoven at 65 ^{o}C for 20 mins without applying any pressure. The glass transition temperature of the non-cross-linked SU-8 is 64 ^{o}C, and at the glass transition temperature or above, SU-8 exhibits excellent self-planarization, which minimizes the edge bead effect as well as other thickness variations. Pressure is applied afterwards throughthe home-made bonder. The material stack is mounted between the two thick Pyrex glass slides. The steel ball and the Belleville washer spread the point force generated by the thumb screw onto the thick Pyrex glass plate. The pressure is higher at the center than at the edges. This gradient pressure distribution avoids the formation of air cavities in between the two SU-8 layers. As the polymer flows, the pressure decreases, which can be compensated by the thermal expansion of the Belleville washers. The sample is kept in a65 ^{o}C vacuum ovenfor 20 hours to allow for polymer to reflow and to squeeze out the trapped air bubbles. After that, the sample is illuminated by 365 nm ultraviolet light through the glass slide to crosslink the SU-8 polymer. Exposure dose isaround150mJ/cm^2. A second long term post exposure bake (PEB) at 65 ^{o}C is done to further crosslink SU-8. After bonding, the silicon handle is removed by DRIE. To control the thermal budget, the silicon handle is mechanically polished down to ~100 μm prior to DRIE, to shorten the etching time. The ICP and the etching time are carefully tuned to achieve an optimized heat dissipation:etch rate trade-off condition. The silicon etch rate of this recipe is around 2.7 μm/cycle. The 3 μm BOX acts as an etch stop layer, which is later removed by hydrofluoric (HF) acid etching. A picture of the transferred SiNM on glass is shown in Fig. 1. The SEM cross section in the inset shows the different layers, with the final SU-8 thickness measured to be 9.4μm. The thickness variation across the entire chip is ~200 nm, due to uneven pressure during the bonding step. The transferred SiNM is examined with an optical microscope, and no visible defects are found.

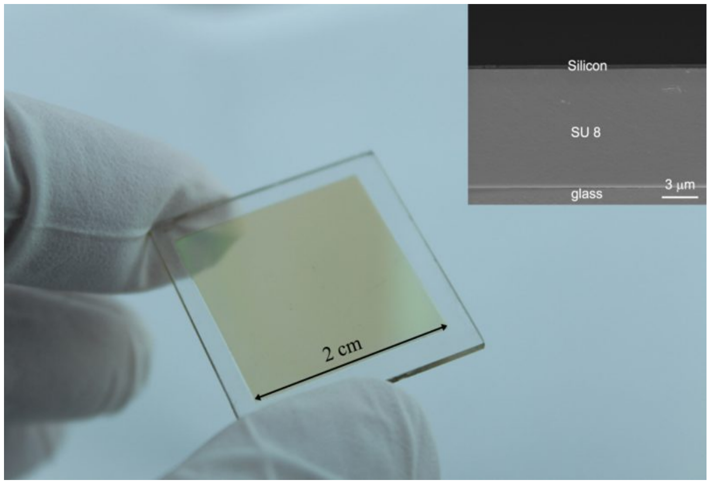

Fig. 1 Microscope image of 2cm x 2cm SiNM transferred on 1mm thick glass substrate. Inset: SEM image of cross section.

The transferred nanomembranecan be patterned using conventional e-beam lithography. The resist ZEP 520 is spin-coated at 6000 rpm for 35s, forming a film of ~300 nm. Due to the CTE mismatch between silicon and SU-8, the resist film, with CTE being optimized to match silicon, is subject to cracking if baked at the standard process temperature of 180 ^{o}C. Therefore, the sample is pre-baked at a lower temperature of 90^{o}C for an extended duration of 30mins to evaporate the solvent. The resist is patterned with JEOL 6000, and then the pattern is transferred onto SiNM through reactive ion etching (RIE).In this work, a slow-light photonic crystal waveguide (PCW), with a period (L) of 405 nm , and a hole diameter (d) 190 nm is patterned on the transferred SiNM. Photonic crystal tapers are utilized at the strip-PCW interfaces in order to minimize the coupling loss into the PCW, thus enabling operation in the high-group index region near the band-edge, which gives much larger delay time and faster tuning based on wavelength tuning.A SEM picture of the fabricated PCW is shown in Fig. 2(a). 17.1μm x 10μm SWG couplers are utilized to couple light into and out of the waveguides [15]. We have previously demonstrated high coupling efficiency of 37.2% into transferred SiNM waveguides from a single mode fiber [15]. The SWG couplers are fabricated simultaneously together with the PCW. An SEM picture of the SWG coupler is shown in Fig. 2(b).

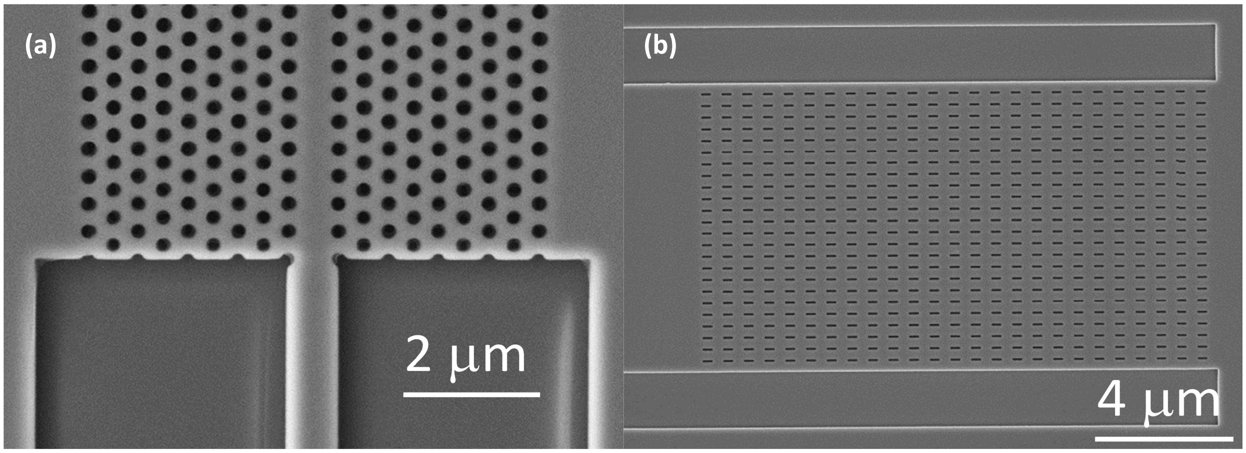

Fig. 2 Scanning electron microscope (SEM) images of (a) slow-light photonic crystal waveguide, and (b) subwavelength grating coupler (SWG) on the transferred SiNM.

In order to accurately measure the group index of the fabricated PCW, a Fourier transform interferometer is also designed and fabricated on the transferred SiNM. A microscope image of the interferometer is shown in Fig. 3. The interferometer consists of a signal arm (S) consisting of 100 μm of the designed PCW; a reference arm (R) consisting of 5.256 mm of a reference strip waveguide; and an interference arm (I) the combines the R and S signals using a Y-splitter.

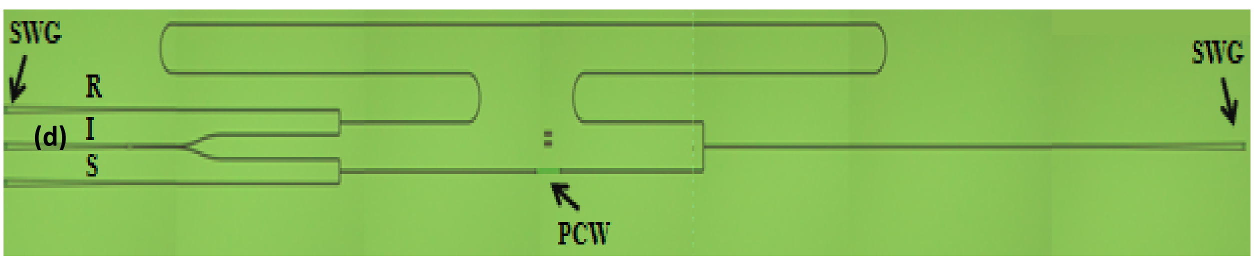

Fig. 3 Optical microscope image of the fabricated Fourier transform interferometer on SiNM:glass

3. DEVICE CHARACTERIZATION

Using the method outlined in ref [17], we measure the group index of the PCW.TE polarized light from a broadband amplified spontaneous emission (ASE) source is coupled into the SiNMdevice containing the PCW waveguide via the grating couplers. The input and output fibers are mounted on two 10^{o} wedges, which are mounted on two xyz stages. The input fiber is a polarization maintaining (PM) fiber whose polarization is controlled via a waveplate-based polarization controller (PC). The output fiber is a conventional single mode fiber with a core diameter of 9 μm. The tilt angle can be adjusted from $0^{o} \sim 20^{o}$. For this design, both the input and output fibers are tilted $\sim 9.4^{o}$ from normal incidence.

The interference signal between the PCW and the reference arm shows a decreasing fringe spacing as we move closer to the band edge. This is indicative of slow-light effect. From this data, the group index is derived, and shown as red dots in Fig. 4. A group index up to 28.5 is measured on the SiNM based PCWs. Based on our previous experimental results [16], wherein a

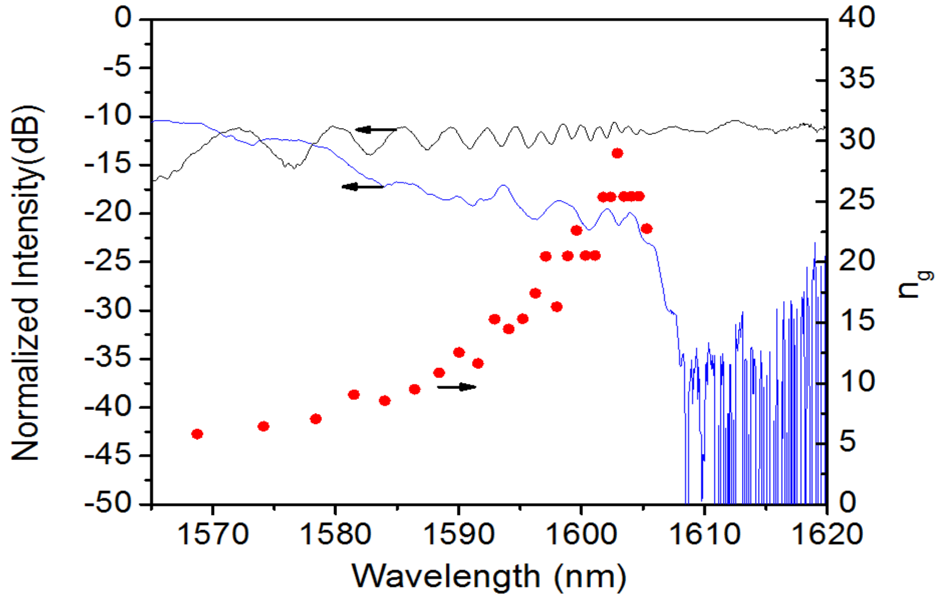

Fig. 4 Measured transmission spectrum from S (blue) and I (black) channels. Calculated group index is shown as red data points.

group index of ~23 was obtained from the transferred PCW delay lines, a time delay larger than 216.7ps can be achieved from a 3mm long PCW structure. Thus, using our scheme, we have successfully demonstrated the idea of the development and working of intricate photonic devices on foreign substrates. Moreover, SWGs prove to be an ideal packaging tool for such devices.

4. CONCLUSION

We have developed a scheme to achieve large area transfer of unpatterned SiNM onto foreign substrates. A light coupling method based on subwavelength grating couplers is utilized to achieve efficient light coupling into the devices. To prove the feasibility of development of compact true-time-delay lines on any substrate, slow-light photonic crystal waveguides are designed and patterned on transferred SiNM. A Fourier transform interferometer is also developed, and group index up to 28.5 is accurately measured for the transferred devices. Such slow-light PCWs can enable achievement of time delay values in excess of 58ps per millimeter of PCW. This demonstration shows great promise for the development of lightweight and conformal compact antenna control systems for air- and space-borne platforms.

5. ACKNOWLEDGMENTS

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